

# A Superwind from Early Post-Red Giant Stars?

Noam Soker<sup>1</sup>, Márcio Catelan<sup>2,3</sup>, Robert T. Rood

*University of Virginia, Department of Astronomy, P.O. Box 3818, Charlottesville, VA  
22903-0818, USA*

Amos Harpaz

*University of Haifa at Oranim, Department of Physics, Oranim, Tivon 36006, Israel.*

## ABSTRACT

We suggest that the gap observed at  $\sim 20,000$  K in the horizontal branches of several Galactic globular clusters is caused by a small amount of extra mass loss which occurs when stars start to “peel off” the red giant branch (RGB), i.e., when their effective temperature starts to increase, even though they may still be on the RGB. We show that the envelope structure of RGB stars which start to peel off is similar to that of late asymptotic giant branch stars known to have a super-wind phase. An analogous super-wind in the RGB peel-off stars could easily lead to the observed gap in the distribution of the hottest HB stars.

*Subject headings:* stars: Hertzsprung-Russell (HR) diagram – stars: horizontal-branch – stars: mass-loss

## 1. INTRODUCTION

Gaps along the principal sequences of globular cluster (GC) color-magnitude diagrams (CMDs) constitute one of the most intriguing problems in the evolution of low-mass stars. Sandage, Katem, & Kristian (1968) first reported that a “major significant” gap was present on the red giant branch (RGB) of M15 (NGC 7078), and subsequently similar features were

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<sup>1</sup>On Sabbatical from the University of Haifa at Oranim, Department of Physics, Oranim, Tivon 36006, Israel.

<sup>2</sup>Hubble Fellow.

<sup>3</sup>Present address: Pontificia Universidad Católica de Chile, Departamento de Astronomía y Astrofísica, Av. Vicuña Mackenna 4860, Santiago 22, Chile

reported in several other GCs. Most prominent among these have been the gaps along the horizontal branch (HB), which is the core helium-burning evolutionary phase immediately following the RGB phase. The HB is thought to constitute a sequence in post-RGB mass (Rood 1973), where stars with progressively lower masses (i.e., with higher mass loss rates on the RGB) end up at hotter and hotter regions on the zero-age HB (ZAHB).

While the statistical significance of the Sandage *et al.* (1968) gap on the M15 RGB has been questioned on the basis of detailed Monte Carlo simulations (Bahcall & Yahil 1972), and while similar arguments (Catelan *et al.* 1998) have been put forward to question the statistical significance of gaps similar to the famous “Newell (1973) gaps” along the HB, it is still possible that some of the detected gaps on the HB may turn out to be real (Ferraro *et al.* 1998; Piotto *et al.* 1999), thereby requiring a physical (rather than purely statistical or mathematical) explanation for their occurrence. For instance, Brown *et al.* (2001) have recently provided a convincing physical explanation for a gap located inside the “extreme HB” (EHB) of NGC 2808 (Bedin *et al.* 2000).

Besides the EHB gap, one cooler gap, presumably located somewhere in the range  $T_{\text{eff,G1}} \approx 10,000 - 12,000$  K, has often been suggested in the literature; this is Newell’s (1973) “gap 1,” or the Ferraro *et al.* (1998) gap “G1.” Note that this gap’s temperature is intriguingly close to the onset of radiative levitation of heavy elements in HB stars, which has been shown to give rise to observable consequences in the CMDs of GCs, particularly in the shorter wavelengths (Grundahl *et al.* 1999). Indeed, Caloi (1999) has suggested a connection between a gap at  $(B-V)_0 = 0$  (which however is substantially cooler than G1) and radiative levitation. While interesting, it remains to be proven that a *real* gap exists at the location of G1 in *all* Galactic GCs with sufficiently hot HB stars, in the same manner that radiative levitation of metals clearly **leads** to identifiable features in the near-UV CMDs of *all* GCs whose HBs contain stars hotter than  $T_{\text{eff}} \approx 11,500$  K. The compilation presented by Catelan *et al.* (1998) shows that the fraction of GCs showing one such gap is relatively small, which strengthens the argument that this gap too may turn out to be the result of a statistical fluctuation.

However, the same argument may not apply to Newell’s (1973) “gap 2,” which appears to be located in the same position as gap G3 in Ferraro *et al.* (1998). This is a gap located at a much hotter region of the HB, near the boundary between the blue HB (BHB) and the EHB, at  $T_{\text{eff,G3}} \approx 20,000$  K. While the number of GCs showing extended blue tails reaching the G3 region is small compared with the number of GCs which have the region around G1 populated, several authors have recently argued that all GCs with sufficiently extended blue tails do seem to show the G3 gap (Ferraro *et al.* 1998; Piotto *et al.* 1999; Brown *et al.* 2001). Ferraro *et al.* argue that such a gap occurs at roughly the same temperature in all

clusters,  $T_{\text{eff,G3}} \simeq 20,000$  K (cf. their Table 2). In contrast, Piotto *et al.* argue that clusters with different metallicity have gap G3 located at somewhat different temperatures and the quantity remaining constant from one case to the next is the ZAHB mass of the observed gaps:  $0.53 M_{\odot} < M < 0.54 M_{\odot}$ . The Piotto *et al.* result is based on  $B$ ,  $V$  photometry which is not well suited for determining the physical parameters of such hot stars. To firmly establish the nature of the gap extensive ultraviolet photometry of a large sample of blue-tail GCs is needed. What is clear now is that all clusters with a substantial HB populations hotter than  $\sim 20,000$  K observed to date show a gap, and that the envelope mass for the stars hotter than G3 is quite small. In any case, our proposed scenario does not depend strongly on the gap being for a constant total stellar mass. It could as well be at a constant envelope mass, and have some dependence on metallicity (although the core mass does not depend strongly on metallicity; Sweigart 1987).

Our goal here is to explore a possible physical reason for the occurrence of gap G3. We shall investigate the requirements on the (ill constrained) RGB mass loss rates for a gap such as the one conjectured by Piotto *et al.* to appear. We propose that stars which start to peel-off the RGB experience a super-wind phase, i.e., an enhanced mass loss rate phase, during the very late RGB phase and early post-RGB phase. Although by peel-off stars one usually refers to stars which have the core helium flash during the post-RGB phase, in the present paper we use the term more loosely, also to characterize all RGB stars which start to move to the left on the HR diagram, i.e., whose surface temperature starts to increase, even though they may still be on the RGB by the time they undergo the helium core flash. From the inner bright shell of planetary nebulae and obscuration of late asymptotic giant branch (AGB) stars, such a super-wind phase is known to exist in late AGB and early post-AGB stars. The AGB super-wind was postulated by Renzini (1981). A super-wind phase seems to occur in some red supergiants which are progenitors of Type II narrow-line supernovae (Fransson *et al.* 2001).

We begin in §2 by evaluating the constraints on the RGB mass loss rate for the production of a gap similar to G3. In §3 we discuss the envelope structure of RGB stars that are near the “peel-off” stage at the tip of the RGB and post-RGB, comparing that against similar computations for AGB stars during their super-wind phase. A summary and discussion are provided in §4.

## 2. THE SUPERWIND POSTULATION

Lower metallicity stars peel-off the RGB at higher temperatures, smaller radii, and have lower opacities compared with higher metallicity RGB stars. In what follows we scale

parameters for the  $[\text{Fe}/\text{H}] = -1.48$  and  $Z = 6 \times 10^{-4}$  model of D’Cruz *et al.* (1996). This model leaves the RGB with  $L \simeq 1800 L_{\odot}$ ,  $T_{\text{eff}} = 4000 \text{ K}$ , and  $R = 90 R_{\odot}$ . By peel-off stars we refer to all stars which have their surface temperature increasing on the RGB, even if a core helium flash occurs while they are still on the RGB. This is more or less the stage where the super-wind occurs in AGB stars. From Castellani & Castellani (1993) we find that RGB stars start to peel-off when their total mass is  $M \simeq 0.5 - 0.6 M_{\odot}$ . Stars that suffer core helium flash during the post-RGB phase, i.e., bona-fide peel-off stars, have much lower masses (D’Cruz *et al.* 1996). We take the duration of the super-wind,  $t_{\text{sw}}$ , to be similar to, or somewhat longer (due to slower evolution of low-mass cores) than, the super-wind phase in AGB stars, namely  $t_{\text{sw}} \simeq t_{\text{sw}} = 10^4 \text{ yr}$ , and scale quantities by their values at the termination of the RGB. The boundary between peel-off and He-flasher stars occurs for  $\eta \simeq 0.7$  (D’Cruz *et al.* 1996; Brown *et al.* 2001), where  $\eta$  determines the mass loss rate via the Reimers (1975a, 1975b) formula. Since we are interested in stars that start to peel off, even if not becoming peel-off stars, we scale with a somewhat lower mass loss rate  $\eta = 0.5$ , to get

$$\dot{M}_{\text{R}} = -6.5 \times 10^{-8} \left( \frac{\eta}{0.5} \right) \left( \frac{L}{1800 L_{\odot}} \right) \left( \frac{R}{90 R_{\odot}} \right) \left( \frac{M}{0.5 M_{\odot}} \right)^{-1} M_{\odot} \text{ yr}^{-1}. \quad (1)$$

Even though we use Reimers’ formula as a reference, it should be noted that any of the alternative analytical mass loss formulae discussed by Catelan (2000) yield qualitatively similar results. To form the observed gap at  $\sim 20,000 \text{ K}$ , we require the peel-off stars to lose extra mass. Using the Piotto *et al.* (1999) result that the gap in different GCs occurs at roughly the stellar mass range of  $0.53 M_{\odot} < M < 0.54 M_{\odot}$ , the required enhanced mass loss rate factor  $\Gamma$  is

$$\Gamma = \frac{\Delta M_{\text{sw}}}{|\dot{M}_{\text{R}}| t_{\text{sw}}} = 15 \left( \frac{\Delta M_{\text{sw}}}{0.01 M_{\odot}} \right) \left( \frac{|\dot{M}_{\text{R}}|}{6.5 \times 10^{-8} M_{\odot} \text{ yr}^{-1}} \right)^{-1} \left( \frac{t_{\text{sw}}}{10^4 \text{ yr}} \right)^{-1}, \quad (2)$$

where  $\Delta M_{\text{sw}}$  is the extra mass that needs to be lost during the super-wind phase. A similar factor, or even larger, is thought to exist in stars leaving the AGB. As the star loses mass, contracts, and heats up, the super-wind ceases. The super wind may last longer than the scaled time here, and the enhanced mass loss factor can be smaller, e.g.,  $\Gamma = 3$  for  $t_{\text{sw}} = 5 \times 10^4 \text{ yr}$ . In any case, after the super-wind gradually ceases, the mass loss resumes its “normal” value (as provided, e.g., by Reimers’ formula). Just as the “normal” mass loss varies from star to star due to differences in some yet unknown parameter like rotation, the super wind probably also varies from star to star. The net effect of the super-wind is to increase somewhat the amount of mass lost by the star. It will not remove the entire envelope, just as the “regular” wind will not. Only stars below the gap have experienced a super-wind. The derivation above suffers from several large uncertainties, but it does suggest that a super-wind may explain the G3 gap.

### 3. ENVELOPE STRUCTURE

One of the reasons for the occurrence of a super-wind in AGB stars may be the shallow density and steep entropy gradients in the envelope (Soker & Harpaz 1999; hereafter SH99). To show from simple arguments that shallow density envelope profiles exist, accompanied by a steep entropy gradient, in peel-off stars, hence we expect them to go through a super-wind phase, we follow the arguments of SH99. The photospheric pressure  $P_p$  and density  $\rho_p$  are determined by the stellar effective temperature  $T_p$ , luminosity, and photospheric opacity  $\kappa$  (e.g., Kippenhahn & Weigert 1990, §10.2). By using the definition of the photosphere as the place where  $\kappa l \rho_p = 2/3$ , where  $l$  is the density scale height, we can write

$$\rho_p = \frac{2}{3} \frac{GM \mu m_H}{k_B} \frac{1}{R^2 \kappa T_p}, \quad (3)$$

where  $k_B$  is the Boltzmann constant and  $\mu m_H$  is the mean mass per particle. At the level of accuracy required here, we can take the pressure and density scale height at the photosphere to be equal. We take the opacity from Alexander & Ferguson (1994), for a temperature of  $T_p \simeq 4000$  K and density of  $\rho \simeq 10^{-9}$  g cm $^{-3}$ . Substituting typical values for peel-off stars, we find the ratio of the photospheric density to the average envelope density  $\rho_a = 3M_e/(4\pi R^3)$  to be

$$\frac{\rho_p}{\rho_a} \simeq 0.026 \left( \frac{R}{90 R_\odot} \right) \left( \frac{\kappa}{10^{-3} \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \left( \frac{T_p}{4000 \text{ K}} \right)^{-1} \left( \frac{M}{0.5 M_\odot} \right) \left( \frac{M_e}{0.04 M_\odot} \right)^{-1}. \quad (4)$$

Since the density increases inward, the density ratio between the photosphere and outer envelope regions is higher (closer to unity), hence a very shallow density gradient exists in the outer envelope regions of upper RGB and early post-RGB stars. In AGB stars with parameters similar to stars with observed super-winds, SH99 find the ratio in equation (4) to be  $\sim 0.25$ . We derive a similar ratio of 0.25 for red supergiants which are thought to have a super-wind (Fransson *et al.* 2001), e.g., VY Canis Majoris (Kastner & Weintraub 1998, and references therein). The structure and properties of RGB stars with low mass envelopes are similar to those of AGB and red supergiant stars. Although such RGB peel-off stars have steeper gradients than the AGB and red supergiants the gradients are much shallower than in “normal” stars, so it is still plausible that these stars have a super-wind phase.

To emphasize the similarity between RGB and AGB stars, we constructed upper RGB and early post-RGB models with the same numerical code that was used to build the AGB models of SH99 (where all details of the calculations can be found), and the same composition was used (solar). We find the same behavior for low metallicity stars, but for a quantitative comparison with AGB stars we present in this short paper the solar metallicity results. In Figure 1 we present the relevant variables in the same form as in SH99, so a direct

comparison can be made. The upper panel is for an RGB stellar model with an envelope mass of  $M_e = 0.1 M_\odot$ . The star at this stage still climbs the RGB (it is a solar metallicity star), and the core has not reached its maximum mass yet. The middle panel presents a star with the same radius, but a lower envelope mass and a more developed core; the star is at its very early post-RGB phase. The envelope in the middle panel has a shallower density and a much steeper entropy gradient compared with the upper panel. The differences in the entropy gradients are largest at the outer  $\sim 20\%$  of the envelope. The lower panel presents a model with a lower envelope mass and later in its post-RGB phase. The radius and envelope mass are lower than those for the middle panel model in such a way that the density gradients are comparable, but the entropy gradient is much steeper in the lower panel. The steepening of the entropy gradients implies a stronger convection. SH99 discuss plausible ways by which these changes can enhance the mass loss rate.

#### 4. SUMMARY

The hottest ( $> 20,000$  K) part of the HB in Galactic globular clusters may be populated by stars which have peeled off, or started to peel off the RGB before the helium flash, i.e., whose surface temperatures increased just before the helium core flash. We suggest that such stars may undergo a super-wind phase analogous to that observed in AGB stars. These stars have the shallow density gradient and steep entropy gradient thought to be important in driving AGB super-winds. Scaling laws suggest that the peel-off star super-winds could provide enough additional mass loss to separate their helium burning progeny from the distribution of normal HB stars whose ancestors underwent the helium flash at the RGB tip.

If this hypothesis is correct, all HBs with a significant population beyond 20,000 K should have a gap in the HB distribution. The presence of the gap should not depend on factors like cluster density or binary fraction. Further ultraviolet photometry of a larger sample of GCs with blue tails is necessary to determine whether the gaps are universal and the physical parameters of the gap. Does the gap occur at constant  $T_{\text{eff}}$ , constant total mass, or constant envelope mass? Coupled with a grid of theoretical models this could point to the key envelope structures which lead to the onset and termination of a RGB super-wind.

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## FIGURE CAPTIONS

**Figure 1:** The envelope structure of three RGB and post-RGB stellar models. The envelope mass of each model is indicated inside the panel. The quantities that are plotted versus the radius are: temperature  $T$  in Kelvin, density  $\rho$  in  $\text{g cm}^{-3}$ , the total mass  $M$  in  $M_{\odot}$ , and the entropy  $S$  in relative units. Note that we treat the region near the photosphere using the Eddington approximation of gray atmosphere, and therefore the values of the density, pressure, and temperature very close to the surface (photosphere) are not accurate. Also, these variables are drawn above the photosphere, since the numerical code has few shells there.



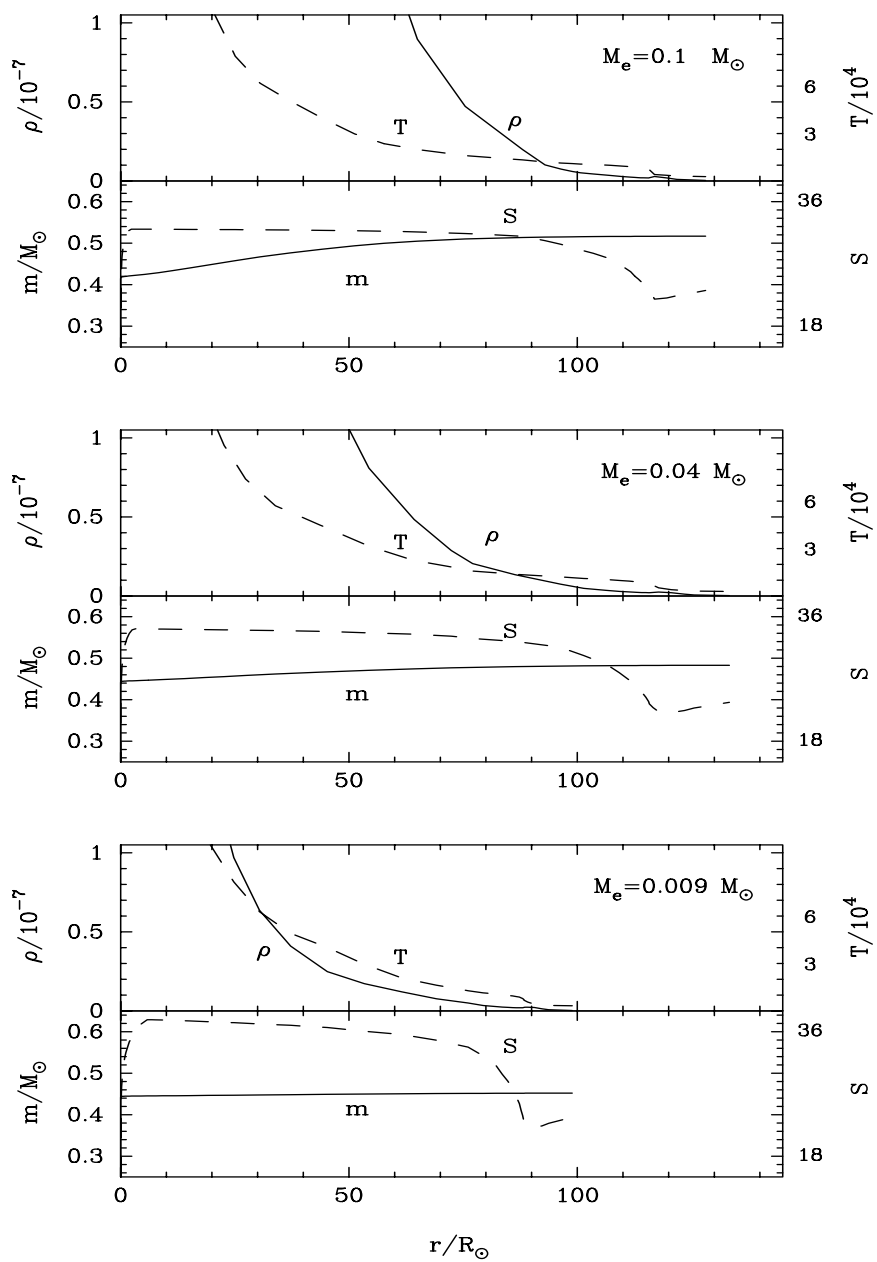


FIG. 1.—